Catchment level modelling of dairy farm adaptation to meet nitrogen loss targets and the value of including plantain as a mitigation

Lydia FARRELL[1]*, Pierre BEUKES[1] and Ryan MILLS[1]
[1]*DairyNZ Ltd, Private Bag 3221, Hamilton 3240, New Zealand*
*Corresponding author: lydia.farrell@dairynz.co.nz

Abstract
Regulations addressing nutrient losses to ground and surface water bodies are increasingly applied at the catchment level, necessitating catchment-level analysis of implementing environmental mitigations. We conducted catchment-scale modelling to predict the production and economic impacts for dairy farms to achieve N (nitrogen) loss targets, using the Dairy Sector Pathways (DSP) model. The Rotorua Lake catchment was used as a case study. The DSP model simulated a population of dairy farms within the catchment based on real farm data, applying 'stacked' mitigation steps over time to meet N leaching targets. The targets required reductions in N leaching per hectare of 31% on average. The study focused on forage plantain as a key low-cost mitigation. When plantain was included, the impacts of farms achieving the final N loss targets were predicted to be substantial, including: 1,100 fewer cows farmed, 790,000 kg fewer milksolids produced annually, and $3.3 million lower annual operating profit across the 26 dairy farms in the catchment. However, without plantain, the economic impacts were even greater, with operating profit reduced by $3.8 million. Adoption of N loss mitigations for significant mandated reductions were predicted to have a large impact on the dairy farming community. Relatively low-cost mitigations such as plantain were demonstrated as valuable for softening these impacts.

Keywords: Dairy Sector Pathways model, farm operating profit, nitrogen leaching, *Plantago lanceolata* L., Rotorua Lake catchment

Introduction
Modelling can be used to simulate farm system changes to reduce N losses to ground and surface water via leaching, and potential impacts on profit. Such modelling can inform the cost effectiveness of individual or combinations of mitigations, as well as highlight the level of system change necessary to achieve a specified nutrient loss target (Chikazhe et al. 2023). Mitigating N leaching from dairy farms is increasingly being addressed at catchment level, i.e., across farms within a landscape that leach nutrients to a specific water body. This approach facilitates collective action by farmers to find solutions and for regulation of these losses.

Farm systems modelling work exploring N leaching and profit impacts of mitigation is often conducted at an individual farm level, typically simulating single or multiple case study farms (Chapman et al. 2020; Chikazhe et al. 2023; Robertson et al. 2023). While the outputs can be extrapolated to inform potential impacts at catchment scale, the diversity of systems, soils, and businesses in the farm population may not be well represented, resulting in considerable uncertainty. The Dairy Sector Pathways (DSP) model was recently developed to simulate a population of dairy farms that evolve over time, adapting their systems to meet N leaching reduction targets, and the associated changes in farm- and population-level bio-physical and economic parameters (Doole et al. 2021). The DSP can be used to 'scale-up' farm-level modelling to look at impacts of farm system changes on a population and community.

The Rotorua Lake catchment is an example of a dairy farming population needing to adapt their systems to meet N leaching targets. The Bay of Plenty Regional Council goal of achieving a sustainable N load of 435 t/year to Rotorua Lake requires dairy farms in the catchment to reduce N leaching losses by an average of 31.3% by 2032/33 relative to a 2017 baseline (BOPRC 2016). The magnitude of these reductions will likely require farms to combine ('stack') multiple N leaching mitigations (Chikazhe et al. 2023). Dairy farms in the Rotorua Lake catchment have been incorporating the grazing herb plantain (*Plantago lanceolata* L.) into their pastures, specifically the cultivar Agritonic that has been confirmed as effective in reducing N leaching by reducing urinary N concentration through dilution and partitioning a smaller proportion of dietary N into urine (Minnée et al. 2020) without negative impacts on production (Pinxterhuis et al. 2023). The recognition of plantain as an N leaching mitigation in modelling used for consent processes is recent (Overseer 2020) and research into its full mitigation potential is ongoing (Pinxterhuis et al. 2023).

The primary objective of this study was to use the DSP model to simulate a representative population of

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dairy farms in the Rotorua Lake catchment, to assess how they can adapt their systems over time to meet N loss targets. The simulation estimated the potential impacts on both production and economic outcomes at the farm and catchment level over time. A secondary objective was to evaluate the value of plantain as an N leaching mitigation strategy by modelling adaptation scenarios with and without plantain as a mitigation option.

Materials and Methods

Dairy Sector Pathways (DSP) model

The Dairy Sector Pathway (DSP) model is a dynamic simulation framework that describes the behaviour of separate dairy farm businesses across time through the implementation of biophysical and economic models (Doole et al. 2021). This enables explicit analysis of how a population of farms is likely to behave over time, depending on a perturbation (e.g., a regulated N leaching target) or adaptations (e.g., farmer responses to achieve the target). The model consists of three components.

Firstly, a farm system model generates a set of biophysical parameters, including fertiliser, feed, production and environmental parameters. A dataset of matched DairyBase and Overseer records (from real farms) is used to generate a set of predicted coefficients for the parameters.

Secondly, DairyBase data (https://www.dairynz.co.nz/business/dairybase/), Dairy Statistics data (https://www.dairynz.co.nz/resources/resource-list/new-zealand-dairy-statistics-2023-24/) and the coefficients generated from the Bayesian model are used as inputs to generate a representative population of simulated farms using the population simulation procedure.

Finally, each farm in the population is run through an annual time-step forecasting procedure. The farm system prediction function calculates the impacts of changes in inputs (e.g., nitrogen in fertiliser, nitrogen in supplementary feed, nitrogen in liquid effluent, stocking rate, irrigation) on the farm system. Financial variables, including cash flows, operating profit, and asset position, are calculated for each simulated farm. This forecasting procedure allows the user to define the policy being analysed and how it transitions over time, pricing assumptions and the actions that can be taken in response to the policy. The model allows farms that are making a financial loss to improve their cost efficiency over time. Farm managers facing low-profit margins and cash deficits will react to their circumstances by investigating parts of the business where the operational cost of production can be reduced (Veix 2022). The DSP accounts for this behaviour, recognizing that dairy farm businesses will improve their cost efficiency when facing tightening margins. Specifically, when a farm's operating margin falls below a minimum threshold, determined by its initial margin, the model enables a gradual improvement in cost efficiency for the farm, equating to a 0.5% improvement in the operating margin per year. This mechanism allows a farm with modest negative margins to recover over time before borrowing exceeds assets. For a farm with more severe financial stress, this mechanism would not be sufficient for them to overcome the cycle of borrowing debt to cover operating costs, resulting in insolvency.

Modelling of Rotorua Lake catchment

The population of simulated farms for the Rotorua Lake catchment was generated by intersecting catchment boundaries with AgriBase data (https://www.asurequality.com/services/other-services/agribase/). Farms with < 30 ha of land or < 50% of farm area falling within the catchment boundary were filtered out. This resulted in 26 dairy dominant farms. To simulate these farms, data from Dairy Statistics for the Rotorua District was used and matched with AgriBase farm sizes to match farms that were approximately the same size. Farm size was defined to include the milking platform, support blocks (i.e., land used to support the milking platform through feed production and grazing for dry cows and youngstock), and non-dairy land (i.e., productive land allocated to non-dairy enterprises such as forestry, horticulture, or drystock grazing). To enable matching with AgriBase data, we assumed that all land used by the simulated farms was owned, as not all participants in AgriBase record their leased land.

The Rotorua Lake catchment has a 2032/33 target N load reduction of 96.4 t for dairy farms in the catchment, as well as Nitrogen Discharge Allocations for dairy blocks (BOPRC 2016). As per the Nitrogen Discharge Allocations (updated for Overseer v6.5.4), dairy blocks leaching above 52.6 kg N/ha, based on 2017 data, must reduce to this upper bound by 2032/33. Blocks leaching between 52.6 and 39.8 kg N/ha must reduce to the lower bound (39.8 kg N/ha) by 2032/33. Blocks below the lower bound are allowed to remain at their 2017 level or increase to the lower bound, if desired (BOPRC 2016; MacCormick 2017).

The initial farm-level N leaching distribution (in kg N/ha) for the 26 representative dairy farms (simulated farms) had to match the observed distribution obtained from BOPRC (Stephanie Fraser, pers. comm., 2024). An optimisation process was used to estimate the initial N leaching for each simulated farm (assumed to be the 2017 baseline/starting value) by using the observed distribution, the dairy reduction target of 96.4 t, an average reduction of 31% across all dairy farms, and the target total dairy N load in 2032/33 as constraints. These estimated baseline/starting N leaching values were sense checked using DSP's bio-physical N cycling model.

The N leaching reduction targets for the two intermediate dates for the Rotorua Lake catchment were modelled at 31.4% (2022/23) and 65.7% (2027/28) of the final target (BOPRC 2016). Furthermore, ten different response timing strategies, i.e., pace of N leaching reductions, were modelled to prevent farms only responding at the specified time points: four describing slow response, three describing linear-like response, and three describing fast response.

For each of the 26 modelled farms N leaching mitigations were sequentially introduced ('stacked') until the N leaching reduction target was met, following a general approach of starting with less costly options that are more easily implemented and more costly options requiring systems changes coming later in the stack (Table 1). Plantain was modelled as the first step in the stack and at three levels to assess its value as a mitigation: no use of plantain (P0) and at 20% (P20) or 30% (P30) of the pasture sward on average across all effective area of the milking platform and support block. The level of 20% plantain has been demonstrated as achievable at farm scale in the Rotorua Lake catchment, while the 30% level is a more ambitious target (Fransen et al. In Press).

The most recent full DairyBase dataset available was the 2017/18 year, thus it was modelled as the starting point. All economic input costs and output prices were held constant over time using 2017-18 data (farm ,gate milk price of $6.65/kg MS) and assumptions used to model the mitigations are outlined in Table 1. Modelling of three real case study farms in the Rotorua Lake catchment in OverseerFM (https://overseer.org.nz/overseerfm/) and Farmax (https://www.farmax.co.nz/) was used to inform the order of mitigations in the stack in Table 1, by comparing each mitigation for the N leaching reduction achieved and its impact on operating profit. The exception was plantain, which was modelled as the first mitigation, to compare the stack with and without its inclusion. This case study modelling was also used to validate DSP predictions of N leaching and profit impacts, and to inform the N leaching reductions for specific mitigations. For example, in step five (removing cropping) the case study outputs were used in the DSP because the DSP has not been developed to simulate N leaching from crops.

Results

Farms meeting the N leaching targets

The DSP-generated dairy farm population for the Rotorua Lake catchment at the 2017/18 start point

Table 1 Mitigations and key assumptions

Mitigation	Key assumptions
1. Plantain; modelled at three levels of pasture sward DM content (0% = P0, 20% = P20, or 30% = P30)	N leaching reduction of 9.8% (P20) or 14.8% (P30), compared with 0% (P0)[1]. Cost of annual broadcasting 3 kg/ha (P20) or 3.5 kg/ha (P30) of plantain seed with fertiliser applications assumed to be $25.99/kg seed across milking platform and support block.
2. 10% reduction in imported feed	Reduce across the season and reduce milksolids production per cow. Reduces direct and associated costs of feed (Neal and Roche 2019).
3. 10% reduction in N fertiliser	Reduce across the season and reduce milksolids production per cow
4. 25% N fertiliser reduction from baseline	Reduce in autumn and send cull cows away earlier
5. Remove cropping from the milking platform	Assume 37% of farms use cropping on 5% of platform (from DairyBase data) and 6% reduction in N leaching[1].
6. 50% N fertiliser reduction from baseline	Reduce across the season and reduce stocking rate
7. 50% imported supplement reduction from baseline	Reduce across the season and reduce stocking rate. Reduces direct and associated costs of feed (Neal and Roche 2019).
8. Change imported feed	Change to supplement with lower crude protein content, i.e. crude protein content from 14% to 8% of DM.
9. Stand-off facility	Applicable to a maximum of 85% of farms (DairyBase data indicated that 15% of farms in Rotorua have existing facilities), utilised 8 and 16 hours/day in autumn and winter, respectively, and assume 14% reduction in N leaching[1]. Costs of $1,500/cow including upgrading effluent, 25-year depreciation, 7% interest rate, and $90/cow annually for woodchip (Chikazhe et al. 2023).
10. Zero N fertiliser	Reduction in stocking rate.
11. Retired land to unharvested pine forestry	Assume forestry N leaching of 3 kg/ha annually and establishment and maintenance costs (Elliott and Sorrell 2002). Reduced variable costs related to dairy enterprise on retired land and included carbon income at $80/tonne.

[1]From modelling of case study farms in Farmax and Overseer.

was diverse in size, (ranging from 150 to 1,191 cows), productivity, (supplying 651 to 1,676 kg MS/ha), and N inputs (applying zero to 190 kg N/ha in fertiliser, Table 2). The farm-level annual N leaching rates simulated by the DSP ranged from 30 to 109 kg N/ha. The predicted average N leaching reductions required for the simulated farms in the catchment was 31% for 2032/33 relative to the start point. The final step of the mitigation stack, land retirement to unharvested pine forest, was predicted to be required of at least four of the 26 farms in the Rotorua Lake by 2032/33 to achieve the target N leaching reductions. Farms requiring the mitigations of no use of N fertiliser and/or land retirement, tended to have modelled N leaching reduction targets above the average of 31% for the catchment (Figure 1). As greater reductions in N leaching were achieved, farm operating profit decreased and the spread of operating profit losses between farms in the population increased. For example, in the P0 scenario, for farms reducing N leaching by less than 31%, the reductions in operating profit ranged from 8 to 14%, while for farms with above-average N leaching reduction targets the reductions in operating profit ranged more widely between farms from 17 to 62%.

Modelled mitigations for N leaching reduction generally involved farm system de-intensification and therefore farms in 2032/33 had on average fewer cows, lower milksolids production, and reduced profitability (operating profit and return on assets) relative to the 2017/18 start point (Table 3). Scaled up to catchment level, these impacts were 265 ha land retired from dairy, 1,500 fewer cows, 1,000 tonnes fewer milksolids sold, and $3.7 million lower operating profit.

The value of plantain

Including plantain in the stack of mitigation strategies helped to cost-effectively reduce nitrogen leaching, making it easier for farms to meet environmental targets. This meant fewer farms had to take more costly measures like retiring land (Table 4). This is shown in Figure 1, where farms reducing N leaching by more than the catchment average of 31% are mostly above the 1:1 line for the P20 and P30 scenarios, i.e., the % reduction in operating profit is less than the % reduction in N leaching. Without plantain most of these farms are below the 1:1 line. At catchment level, the benefits of the P20 scenario compared with P0 include approximately 400 more cows, 200,000 kg more milksolids sold, and $500,000 more operating profit in the 2032/33 year (Table 3). The profitability benefits of including plantain were estimated for every year as farms implement the mitigation stack, where the cumulative difference in operating profit between the P0 and P20 scenarios totalled a nominal value of $17.9 million to 2032/33, and this benefit would be expected to continue beyond 2032/33 when farms will be maintaining N leaching at target level.

Discussion

The DSP output shows diversity between farms for the impacts of adapting to meet N leaching targets, as influenced by their starting position – such as initial system intensity, N leaching level and profitability.

Table 2 Summary statistics generated by the DSP of the simulated dairy farm population at the start point in 2017/18 and DSP-generated N leaching reductions required to meet 2032/33 targets. SD = Standard Deviation.

	Mean	Median	SD	Min.	Max.
Farm size (ha)	210	193	126	54	604
Effective farm size (ha)	173	158	94	54	425
Peak herd size (head)	474	420	259	150	1,191
Stocking rate (cows/ha)	2.7	2.8	0.17	2.4	3.1
Milksolids sold (kg/ha)	1,115	1,084	298.9	651	1,676
Milksolids sold (kg/cow)	408	387	106.8	252	594
N fertiliser (kg/ha)	54	41	57	0	190
Pasture eaten (t DM/ha)	11.0	10.5	1.6	8.8	15.3
Supplement eaten (t DM/ha)	2.9	2.4	1.8	0.6	6.2
Debt to asset ratio (%)	54.2	57	0.14	21.8	89.6
N leaching in 2017/18 (kg N/ha)	58.9	56.3	18.4	30.3	109.3
N leaching target for 2032/33 (kg N/ha)	39.6	37.2	9.7	22.9	60.0
N leaching reduction required for 2032/33 (%)	31	32	12	7	47

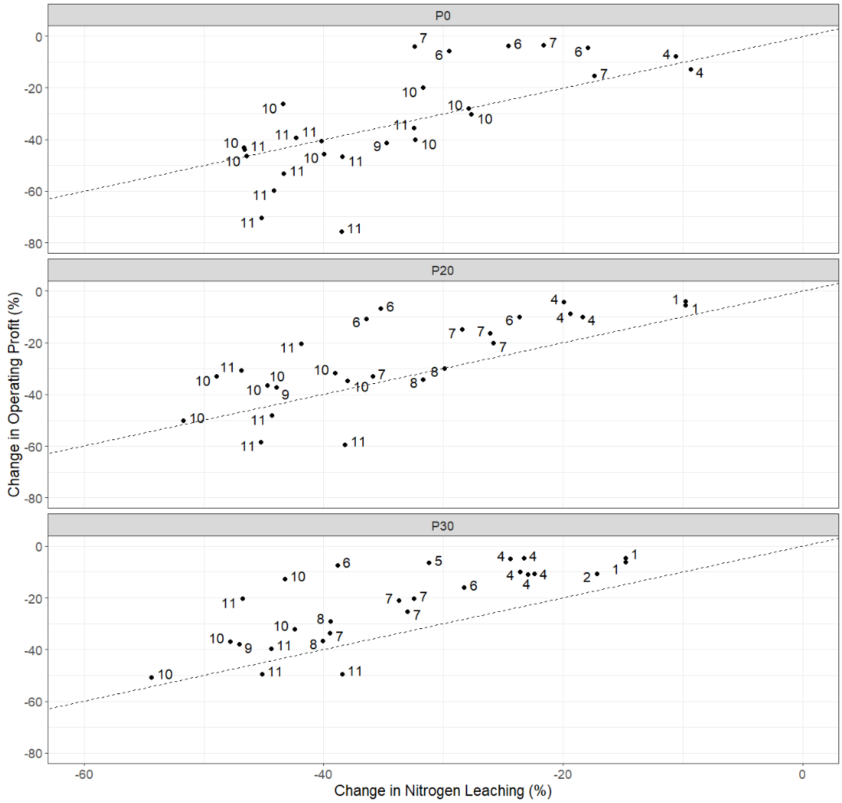

Figure 1 Predicted change in N leaching (%) versus change in operating profit (%) for simulated individual dairy farms in the Rotorua Lake catchment by the 2032/33 target date compared with a 2017/18 baseline. The label indicates the last mitigation option used to achieve the farm target as detailed in Table 1. The dashed line is the 1:1 line. The three scenarios are: with no plantain (P0) or with plantain at 20% (P20) or 30% (P30) of pasture composition (% of dry matter on average across the farm) as part of the mitigation packages.

For example, farms initially applying high rates of N fertiliser with low apparent response rates, i.e., 190 kg/ha/year and 10 kg DM/kg N, were predicted to achieve large N leaching reductions through reducing N fertiliser inputs with profit impacts that were smaller than for other modelled farms. Previous modelling of ten case study farms in Southland predicted 15% to 40% reductions in operating profit to achieve 40% N leaching reduction and when scaled up to represent dairy farms with diverse typologies in a catchment this reduction was 38% (Beukes et al. 2023). This is comparable to the current study modelling a different catchment predicting farm-level operating profit reductions averaging 36% for similar N leaching reductions (Figure 1). The accuracy of the DSP model predictions is influenced by the model inputs, such as the statistics informing the simulated farm population and the assumptions around adaptation. A recent sensitivity analysis of modelling stacked N leaching mitigations showed how different assumptions change the predicted impacts, such as farm N leaching reductions varying from 43% to 50% and operating profit reductions varying from 7 to 15%, when economic and physical input parameters were changed to reflect real-world uncertainties (Chikazhe et al. 2024). The current study used economic and physical inputs from 2017/18) only, which could be varied in future work using the DSP to indicate a range of possible outcomes.

The impacts on profitability for farms to meet the N leaching reduction targets were large and while no farm businesses were simulated as going insolvent during the period of 2017/18 to 2032/33, modelling to 'steady state' ten years beyond the final target date did predict insolvency for one farm when plantain was not available as a mitigation. All other farms generated enough revenue to cover their operating costs as well as interest, rent, drawings, tax, and capital expenses. Surplus cash was used to reduce their debt and their overall financial stability improved over time. Previous modelling of the Rotorua Lake catchment meeting N loss targets predicted a reduction in dairy land, and that remaining dairy farms would have fewer cows, lower N

Table 3 Predicted average farm performance metrics (based on 2017/18 prices) for a simulated dairy farm population in the Rotorua Lake catchment adapting to N leaching reduction targets over time, modelling with no plantain (P0) or with plantain at 20% (P20) or 30% (P30) of pasture DM on average across the farm as part of the N leaching mitigation packages.

	2017/18	2022/23			2027/28			2032/33		
Metric	Start point	P0	P20	P30	P0	P20	P30	P0	P20	P30
Farm-level parameters										
Milksolids production (kg/ha)	1115	1035	1091	1113	949	1027	1063	897	943	969
Gross farm revenue ($/ha)	7927	7377	7767	7912	6806	7334	7573	6466	6778	6953
Operating profit ($/ha)	2547	2303	2381	2433	2046	2179	2263	1683	1858	1969
Operating expenses ($/ha)	5380	5074	5386	5479	4760	5155	5310	4783	4920	4984
Operating profit margin	32.4%	31.5%	30.8%	30.9%	30.1%	29.9%	30.1%	26.7%	27.4%	28.2%
Closing term liabilities ($/kg MS)	26.5	27.8	26.3	25.9	29.8	27.5	26.6	32.7	29.9	28.8
Debt to asset ratio (%)	54.2%	51.1%	51.0%	50.8%	49.1%	48.4%	47.7%	49.3%	47.7%	46.9%
Return on assets (%)	3.3%	3.0%	2.9%	3.1%	2.7%	3.0%	3.1%	2.1%	2.3%	2.5%
Carbon sequestration revenue ($/ ha)[1]	0	0	0	0	0	0	0	38	6	2
Catchment-level Parameters										
Dairy farm area (ha)	4498	4498	4498	4498	4457	4498	4498	4229	4380	4443
Cow numbers (head)	12 327	11 955	12 312	12 327	11 373	11 904	12 034	10 782	11 211	11 423
Milksolids produced (tonnes)	4759	4398	4638	4748	4005	4332	4497	3752	3954	4062
Operating profit ($ millions)	11.3	10.2	10.5	10.8	8.9	9.5	10.0	7.4	8.0	8.5

[1]Carbon sequestration income from land retired to forestry was estimated separately to the operating profit predictions above.

Table 4 The numbers of dairy farms implementing different N leaching mitigations starting with no plantain (P0) or with plantain at 20% (P20) or 30% (P30) of pasture DM on average across the farm in the pastures for three target dates for N leaching reductions.

	2022/23			2027/28			2032/33		
	P0	**P20**	**P30**	**P0**	**P20**	**P30**	**P0**	**P20**	**P30**
1. Plantain	0	26	26	0	26	26	0	26	26
2. 10% less supplement	26	16	5	26	24	19	26	24	24
3. 10% less N fertiliser	25	16	4	26	23	17	26	24	23
4. Less autumn N fertiliser	25	13	2	26	23	16	26	24	23
5. Remove cropping	7	1	0	9	7	6	9	8	8
6. 50% less N fertiliser	10	0	0	21	15	9	24	21	17
7. 50% less supplement	5	0	0	19	8	5	21	18	15
8. Low protein supplement	1	0	0	10	5	2	18	14	11
9. Stand-off facility	4	4	4	5	4	4	6	5	5
10. Zero N fertiliser	0	0	0	7	5	2	17	11	8
11. Retire land	0	0	0	4	0	0	9	5	4

fertiliser and imported supplement feed use, and fewer people employed on-farm, while being less profitable (Parsons et al. 2015). Whether the economic impacts for dairy farms in Rotorua Lake will be similar to the predictions in the current study will depend on factors including farm behaviour beyond what was modelled such as choosing to change land use to a drystock enterprise, modelled mitigations being more effective for reducing N leaching reduction and/or less costly than modelled, and the potential future availability of more cost-effective mitigations than those modelled.

Selection of mitigations to model in a stack significantly affects the overall predictions of N leaching reductions and profit impacts (Beukes et al. 2024). Mitigations that were not included in the current modelling include improving efficiencies such as changes in tactical N fertiliser use or retirement of land with low pasture yield with minimal or nil impact on farm productivity. Such mitigations could be modelled using information from case study farm-level modelling to inform assumptions in the DSP, as was done for multiple mitigations included in the current analysis. However, this would require broad assumptions of applicability within the catchment, introducing large uncertainties. The case study farm-level modelling is also valuable to conduct alongside catchment-level work for community engagement when collaborating with farmers and communicating results.

The modelling quantified many of the benefits of plantain as a cost-effective N leaching mitigation, such as maintaining production and profitability to a higher level compared with the scenario where plantain was not available. The economic benefits predicted for the dairy farms in the catchment would be expected to have positive impacts for the wider community (Sense Partners 2023). Some less easily quantified benefits of plantain were also demonstrated in this study, where farms could meet N leaching targets while implementing fewer of the N leaching mitigations with associated farm system change. Some mitigations required large reductions in imported feed, N fertiliser, improved management of stand-off infrastructure, or land-use change to forestry. Avoiding these mitigations allows farmers the flexibility to operate a resilient system that aligns with their personal approach. The predicted value of plantain as a mitigation could be higher than currently modelled, as current research is demonstrating further N leaching reduction potential through nitrification inhibition and reduced drainage in the soil (Carlton et al. 2019; Petersen et al. 2023; Egan et al. 2025).

The Rotorua Lake catchment sustainable N load and council-mandated farm-level N leaching reduction targets have been established and in effect for several years (BOPRC 2016). Many catchments in New Zealand are currently operating under uncertainty regarding regulations likely incoming for their catchment and associated timelines. Modelling of a population of farms in a catchment or region using tools such as the DSP can inform communities and regulators of potential impacts during consultation and decision-making.

Practical implications

This study demonstrated the value of a modelling approach that simulates a population of farms in a catchment, capturing the diversity of systems and how they can adapt to regulation through time. We recommend that this approach can be used in future modelling exercises for catchments where change is required for a population of dairy farms and for the assessment of the value of specific mitigations or tools.

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